OPTIMIZED GEAR PERFORMANCE BY ALLOY MODIFICATION OF CARBURIZING STEELS FOR APPLICATION IN LARGE GEAR BOXES

Th. Tobie[1], F. Hippenstiel[2] and H. Mohrbacher[3]

[1]FZG – Gear Research Centre, Technische Universität München,
Boltzmannstr. 15, 85748 Garching, Germany
[2]BGH Edelstahl Siegen GmbH, Siegen, Germany
[3]NiobelCon bvba, Swaenebeecklaan 5, 2970 Schilde, Belgium

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Abstract

Both the tooth root and tooth flank load carrying capacities are parameters that decisively influence gear size, as well as gearbox design. The principal requirement of all modern gearboxes is to comply with the demands for steadily increasing power density and to simultaneously offer high reliability of their components. Consequently, the required performance spectrum of materials used for such components is very high. For larger gear sizes, the loads and stresses increase at both surface and sub-surface locations within the gear tooth. Thus, the material properties and particularly the strength, increase in importance at greater material depths below the surface.

The choice of appropriate alloying elements in high performance carburizing steels, in combination with an appropriate heat treatment, allows the adjustment and optimization of strength properties over the material depth. Thereby, the requirements of highly loaded, large gears can be met and a sufficiently high load carrying capacity provided.

This paper initially gives an overview of the main failure modes of case carburized gears resulting from material fatigue at the surface and subsurface locations. Furthermore, the underlying load and stress mechanisms, specifically in relation to the gear size, are discussed as these considerations principally define the required material properties. Subsequently, the principles of newly developed, as well as modified, alloy concepts for optimized gear steels with high load carrying capacity are presented. In particular, the impact of modification of the bulk alloying elements molybdenum, manganese and nickel, as well as that of the microalloying element niobium, was investigated. Furthermore, an evaluation of the relevant material properties of these modified steel grades and a comparison to typical reference grades for gears are presented.

In experimental work, the load carrying capacities of tooth root and flank were determined using a pulsator, as well as an FZG back-to-back test rig. The results demonstrate the effectiveness of these innovative, new alloy concepts. Furthermore, the test results are compared to the current state-of-the-art and benchmarked against established load carrying characteristics of gears manufactured from conventional reference steel grades.

Introduction

Power transmitting gears for modern gearboxes are nowadays nearly always made of case carburized steels, which are particularly suitable for withstanding high local stresses without suffering damage. The properties of the base material in combination with an adequate heat treatment are key factors to ensure a sufficiently high load carrying capacity, as well as a high reliability of the components over the required gearbox lifetime. Gears are generally case carburized to increase surface hardness, to improve wear resistance and to achieve high contact and bending strengths. The heat treatment involved in case carburizing is an exceedingly demanding process, requiring a high level of technical knowledge, as well as a profound understanding of the material characteristics.

Gears and gearboxes are used for a wide range of applications. For example, high-power wind turbines usually have a gearbox transforming the low speed rotor shaft rotation to a higher speed required by the generator. Approximately 85 percent of all windmills are equipped with a gearbox. Usually such gearboxes are designed as one- or two-stage planetary transmissions. These gearboxes have been gradually increasing in size over recent years owing to the up-scaling of individual turbine sizes. In combination with this growth in size, the economic and qualitative optimization of the entire manufacturing chain is of high importance. The gears in wind turbines are sometimes exposed to extremely high loads at the gear flanks and in the tooth root of the gear teeth, for example, during sudden changes of wind speed or hard stops. Many failures and breakdowns of wind turbines, accordingly, originate in the gearbox, leading to significant outages and replacement costs. The powertrain of a windmill accounts for approximately 25 percent of the total equipment cost.

In the mining industry, gears and gearboxes can be found in a variety of different applications along the entire process chain, such as conveyor drives for extraction, gearboxes for mill drive systems in the processing stage, or gearboxes for stackers/reclaimers and special trucks for the transportation process. Most of the gears in these applications have to transmit a high torque and are often subjected to demanding operating conditions and have to achieve a long service life. Consequently, large sized gears can be found in many of these products.

The general requirements for high performance gear components are a hard case providing adequate fatigue strength, as well as wear resistance and a tough core preventing brittle failure under high impact loads [1]. Accordingly, various alloy concepts, as well as thermomechanical and thermochemical treatments have been developed to achieve this property combination. Alloy concepts for medium- and large-size gear applications vary significantly in different markets owing to historical drivers (eg. automotive, machine building, military), and practical experience as well as local availability of alloying elements (Table I).

Table I. Major Carburizing Steel Grades for Medium- and Large-size Gears
in Various Geographical Markets

Steel Grade	Standard		C	Si	Mn	P	S	Cr	Mo	Ni	Region
20MnCr5	EN 10084 (1.7147)	min.	0.17	-	1.10	-	-	1.00	-	-	Western Europe
		max.	0.22	0.40	1.40	0.035	0.035	1.30			
18CrNiMo7-6	EN 10084 (1.6587)	min.	0.15	-	0.50	-	-	1.50	0.25	1.40	
		max.	0.21	0.40	0.90	0.025	0.035	1.80	0.35	1.70	
15CrNi6	EN 10084 (1.5919)	min.	0.14	-	0.40	-	-	1.40	-	1.40	France, Germany
		max.	0.19	0.40	0.60	0.035	0.035	1.70		1.70	
17NiCrMo6-4	EN 10084 (1.6566)	min.	0.14	-	0.60	-	-	0.80	0.15	1.20	Italy, France
		max.	0.20	0.40	0.90	0.025	0.035	1.10	0.25	1.50	
SAE 8620	SAE J1249	min.	0.18	0.15	0.70	-	-	0.40	0.15	0.40	North America
		max.	0.23	0.35	0.90	0.030	0.040	0.60	0.25	0.70	
SAE 9310	SAE J1249	min.	0.08	0.15	0.45	-	-	1.00	0.08	3.00	
		max.	0.13	0.35	0.65	0.025	0.040	1.40	0.15	3.50	
20CrMnTi*	GB T 3077 - 1999	min.	0.17	0.17	0.80	-	-	1.00	0.00	-	China
		max.	0.23	0.37	1.10	0.035	0.035	1.30	0.15	0.30	
20CrMnMo	GB T 3077 – 1999	min.	0.17	0.17	0.90	-	-	1.10	0.20	-	
		max.	0.23	0.37	1.20	0.025	0.035	1.40	0.30	0.30	
SCM420	JIS 64105	min.	0.18	0.15	0.60	-	-	0.90	0.15	-	Japan
		max.	0.23	0.35	0.85	0.030	0.030	1.20	0.30		

*0.04-0.10%Ti

Carburizing steels must comply with the following key requirements in view of component properties and durability:

- Chemical composition/hardenability;
- Homogeneity/microscopic and macroscopic cleanness;
- Mechanical properties (tensile strength, fatigue strength and toughness);
- Wear resistance, contact fatigue strength, bending strength and vibration resistance;
- High and uniform dimensional stability [2].

DIN EN 10084 and ISO 683-11 [3,4] specify the technical delivery conditions for carburizing steels. In addition to the classification and designation of the steel grades, production processes, property requirements (eg. hardenability ranges), testing and inspection procedures are also specified. As well as these general standards, many end users have issued proprietary delivery specifications, which describe particular demands (eg. austenite grain size) in more detail. This is a result of the many possible processing routes for the production of carburized components. Depending on the component requirements, different sequences of annealing, hardening and machining are used, Figure 1. For instance, when a high dimensional stability of the component is needed, pre-hardening is performed before, and stress relieving is performed after, machining. It is, hence, essential to take the entire process chain into consideration when optimizing the material. For the design of large-scale gearboxes, steel grades are commonly selected according to the requirements specified in DIN 3990/ISO 6336, part 5 [5,6]. Figure 2 indicates, as an example, the anticipated tooth root endurance strength of various steel alloys and heat treatment concepts. Within the strength ranges, in general three quality levels can be distinguished: grade ML stands for the minimum requirement; grade MQ represents requirements which can be met by experienced manufacturers at moderate cost; grade ME represents requirements which must be aimed at when higher allowable stresses are desirable, Figure 2, (within each colored area the upper bound represents the strength level for ME requirements and the lower bound for ML requirements. The lines within the colored region represent the strength level for MQ requirements.) It is obvious that the highest strength values are achievable for case carburized gears of quality grade ME. The diagram relates an easily measurable property such as case surface hardness to a complex system property, such as the tooth root endurance strength. The fact that for a given surface hardness a rather wide range of tooth root endurance strength levels can be obtained, suggests that alloy composition, microstructure and thermochemical treatment have an extremely high impact on the actual gear performance. Another system property of high importance for gear durability is the resistance to gear flank failures, such as pitting, and micropitting, as well as tooth flank fracture. High contact pressure, the status of lubrication, material properties, microstructure and chemical composition influence these system properties. Also, with respect to the flank load carrying capacity, case carburized materials of the highest quality level (ME) typically show the highest achievable strength values.

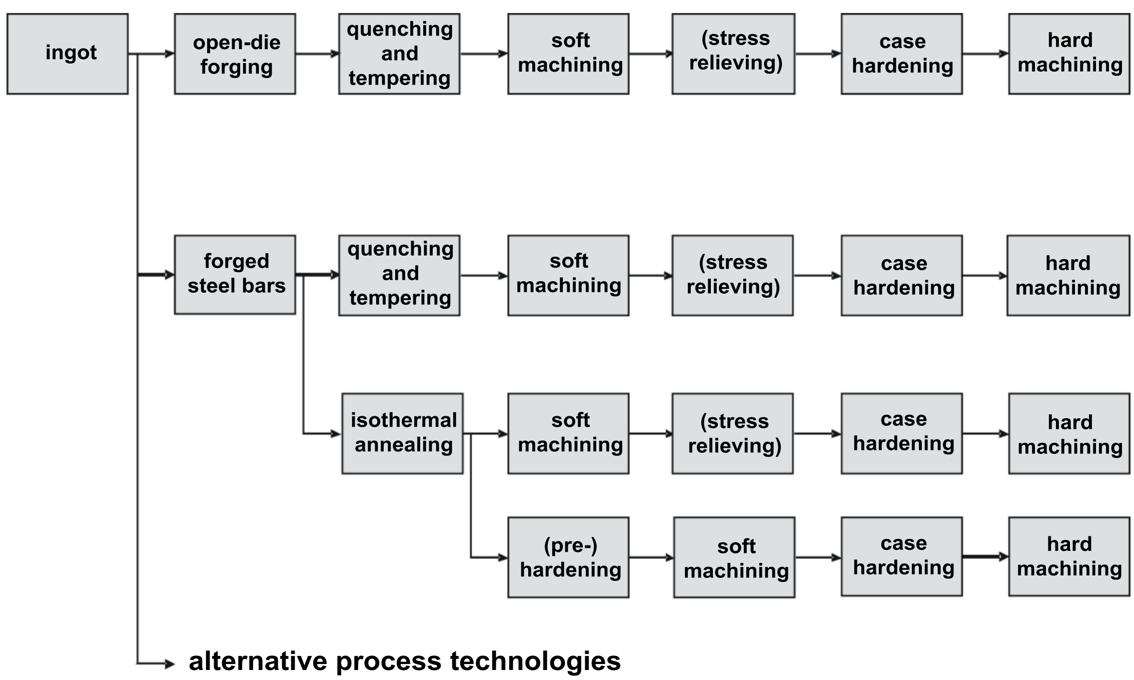
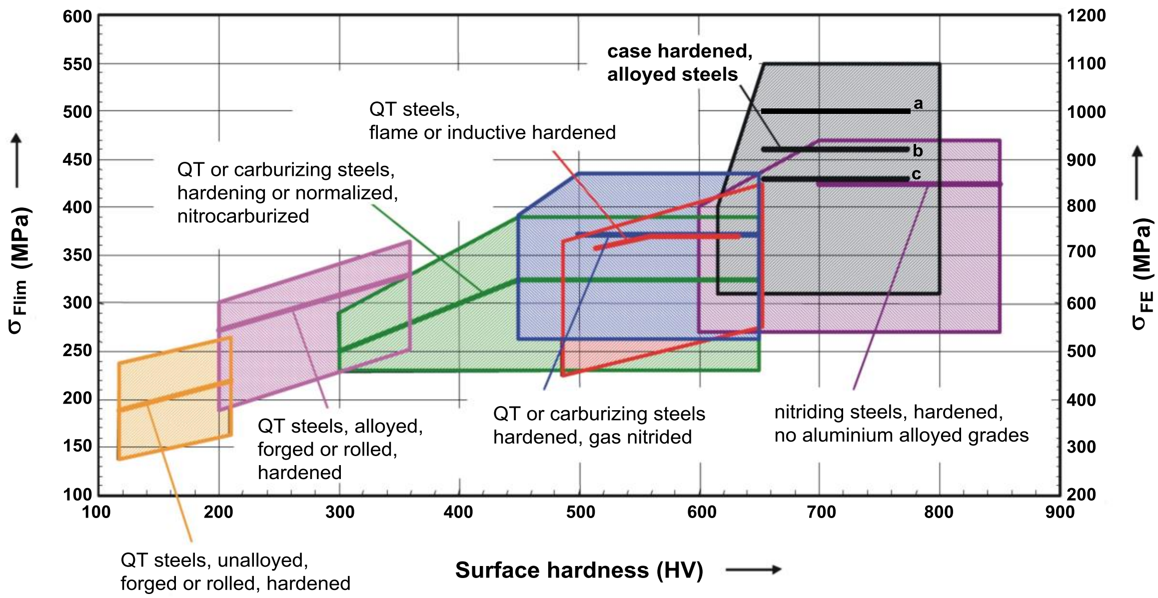


Figure 1. Typical processing routes for manufacturing of case hardened components.



a Core hardness ≥ 30 HRC
b Core hardness ≥ 25 HRC Jominy hardenability at J = 12 mm ≥ HRC 28.
c Core hardness ≥ 25 HRC Jominy hardenability at J = 12 mm < HRC 28.

Figure 2. Tooth root load carrying capacity - allowable bending stress numbers according to ISO 6336-5 and indication of quality levels (ML, MQ, ME) [6].

For both vehicle and industrial transmissions, further optimization of gear steels towards better performance under demanding conditions is necessary. This is in part motivated by the need for reducing fuel consumption and emissions. In addition, a higher load bearing capacity is required at the surface in the near surface case, as well as at greater depths below the surface. A secondary target is to design efficient alloying concepts taking the entire processing route into consideration, including modified or innovative heat treatments. A fundamental way of dealing with these demands is to adjust the chemical composition of carburizing steels. In this respect, one can principally define two approaches. An economically driven approach aims at achieving a defined performance spectrum with a reduced alloy cost concept, whereas a performance driven approach targets superior properties at equal or moderately increased cost. The current work considers both approaches, focusing on modified molybdenum-based alloy concepts, including niobium microalloying. Thereby, innovative heat treatment conditions have also been tested.

Optimization Strategy for Carburizing Steels

Background: Gear Fatigue Failure Modes and Failure Mechanism

The gear load carrying capacity, in general, can be limited by different failure modes. Each failure mode is decisively influenced by the gear design, the material characteristics, the operating conditions and the gear lubricant performance. Nevertheless, each failure mode is influenced by different physical parameters and is subject to different failure mechanisms. For a specific gear design, a clear understanding of the underlying mechanism and the relevant load and stress conditions is required. This allows a material with optimum properties to be selected to permit the gear to be manufactured with the required high load carrying capacity. Gear failures can basically be characterized as either material fatigue related failures or non-fatigue failure modes, which are primarily due to tribological problems in the lubricated contact zone. Furthermore, a differentiation of gear failures is possible depending on the failure initiation site, on the one hand with regard to the location on the gear - at the gear flank or in the tooth root area – and on the other hand with regard to the crack initiation site in the material volume - at the surface, in the case hardened zone or at greater material depth. This can result in different material property requirements in different areas. Figure 3 shows the main gear failure modes related to material fatigue.

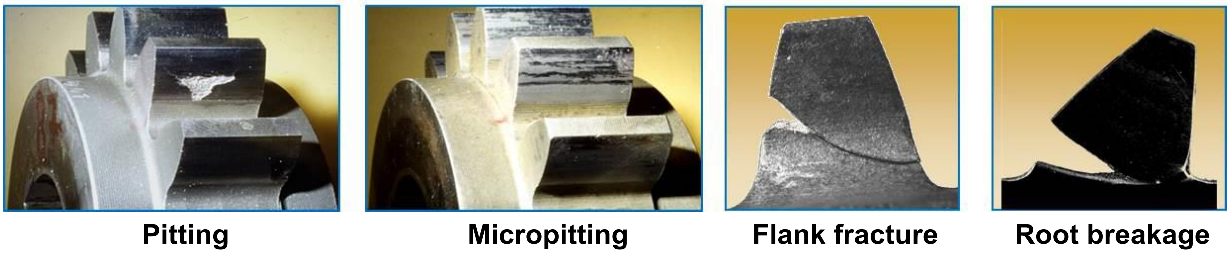


Figure 3. Main gear fatigue failure modes.

Pitting and tooth root breakage are the classical fatigue failure modes of gears. Both failure types are usually initiated at the surface or close to the surface and characterized by a crack that propagates further into the material. Whereas the pitting load capacity is strongly influenced by the Hertzian contact stresses in the gear contact zone, the tooth root strength is related to bending stresses in the root fillet. Differences in the nature of contact and bending stresses may result in different requirements regarding the material properties in relevant material areas, see also Figure 5.

Additionally, the failure mode of micropitting can influence the gear performance. Micropitting is most often observed on the surface of the loaded gear flank under unfavorable lubrication conditions. Nevertheless, micropitting is recognized as a fatigue failure mode but with crack propagation limited to the near surface material. Consequently, micropitting is influenced by the material characteristics specific to the surface and very close to the surface. Furthermore, the contact load at the flank surface also induces stresses at a greater material depth below the surface. If these stresses exceed the available local strength of the material, subsequent failures with crack initiation below the surface may arise. Such failures are referred to in the literature as tooth interior fatigue fracture (TIFF), tooth flank fracture or subsurface fatigue. As the load induced stresses at greater material depth increase with increasing gear size, the strength properties of the material at greater material depth gain more importance for larger gears.

The stress condition in a gear tooth is basically related to the tooth normal force acting in the gear contact zone which depends on the applied torque. This tooth normal force causes contact stresses at the gear flank and bending stresses especially in the root fillet, Figure 4. Further stresses arise depending on the gear geometry, the operating conditions and the manufacturing process.

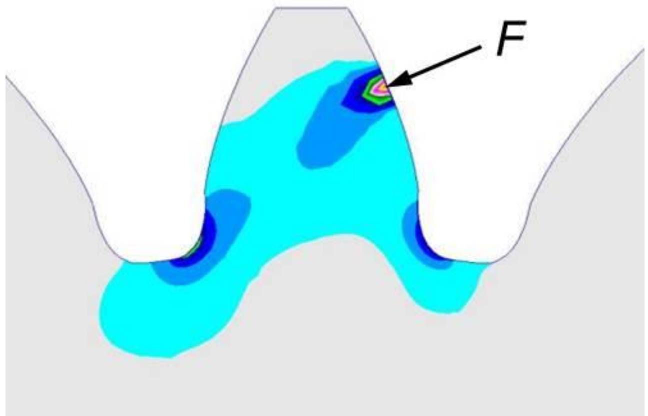
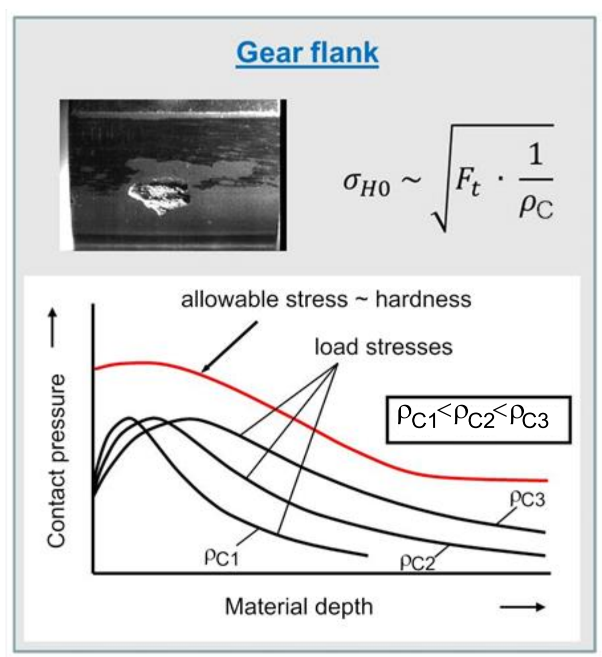


Figure 4. General stress condition inside a gear tooth (F – tooth normal force).

Basically, increasing the gear size allows transmission of a higher torque. Nevertheless, load induced stresses at greater material depth also increase with increasing gear size, even if the maximum stress value is comparable. Figure 5 clearly demonstrates the distribution of the relevant stresses over material depth for different gear sizes. It is obvious that with increasing gear size, expressed by the radius of curvature, ρ_C, for the gear flank, and the gear module, m_n, for the tooth root, an adjustment of the hardness profile is necessary. Consequently, with increasing gear size an increased case hardening depth is required. The influence of case hardening depth (CHD) on the pitting and bending strength of gears is shown in Figure 6.

(a)



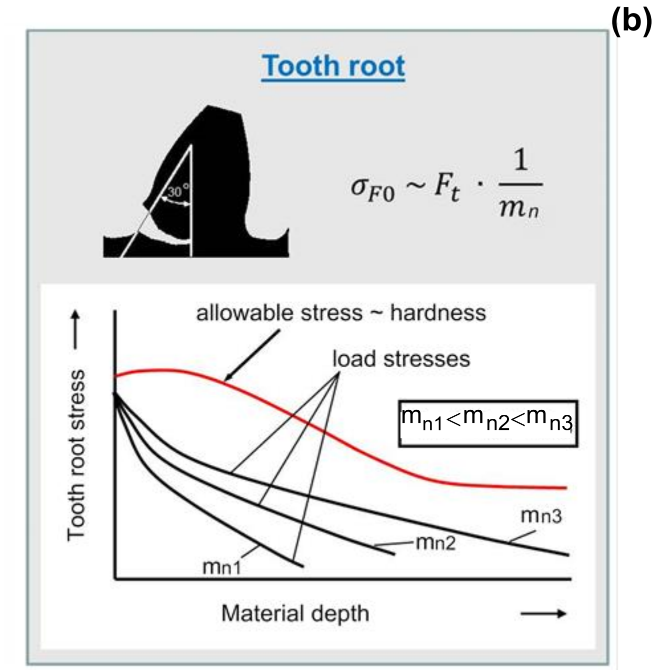
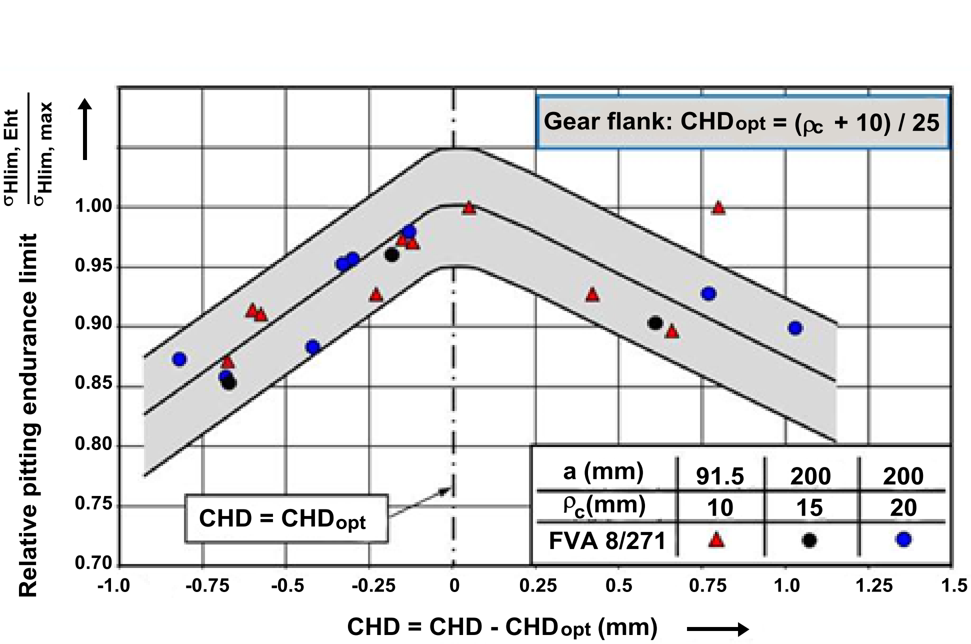


Figure 5. Principles of stress and strength condition depending on gear size;
(a) at the gear flank, (b) at the tooth root [30] (σ_{H0} – nominal contact stress at pitch point, σ_{F0} – nominal tooth root bending stress, F_t – nominal tangential load).



(b)

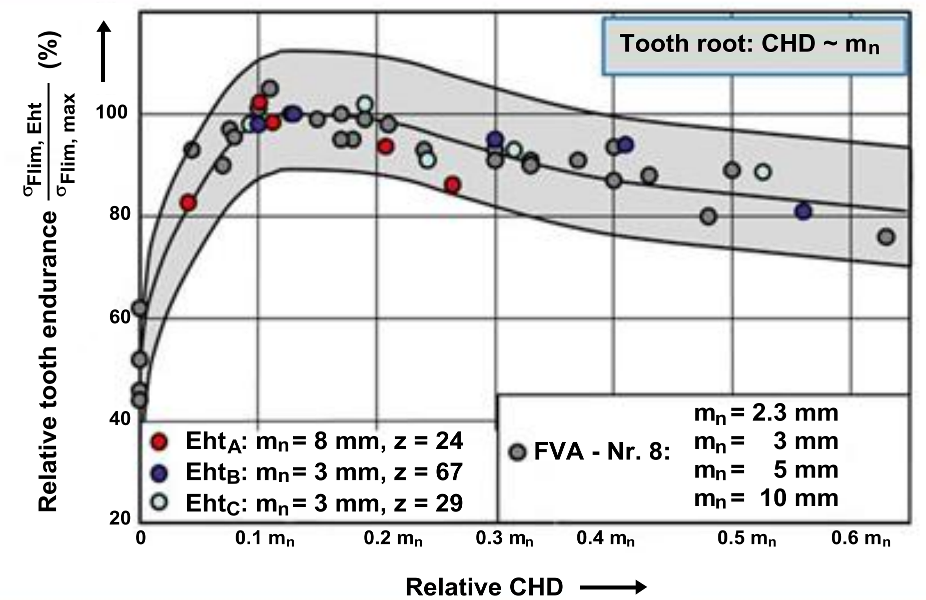
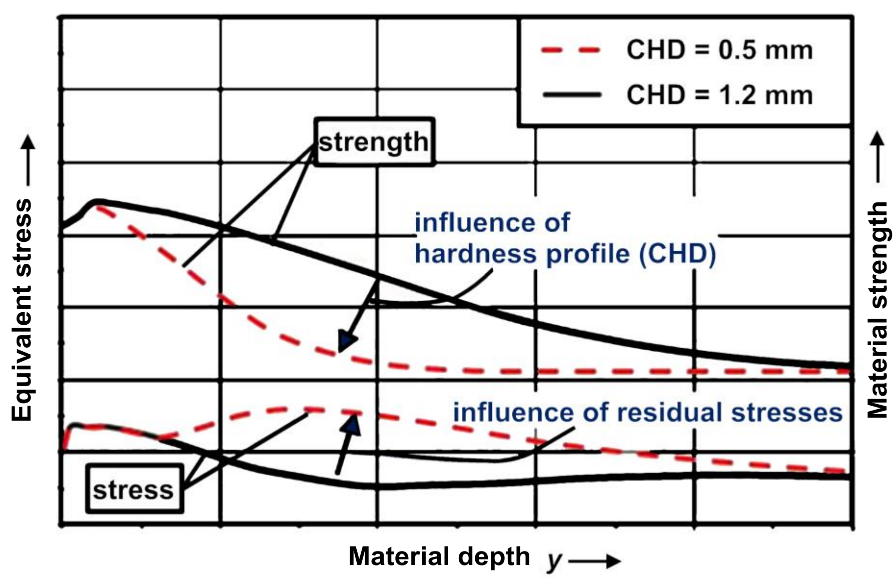


Figure 6. Influence of CHD on; (a) pitting and (b) bending strength of case carburized gears [31] (a – center distance; z – number of teeth; FVA 8/271 – relevant research project number of German research association FVA; Eht – old symbol for CHD).

The strong influence of CHD on the local material exposure A_{FB}, defined as the ratio of locally occurring equivalent stresses to locally available strength, of the gear flank is shown in Figure 7.

(a)



(b)

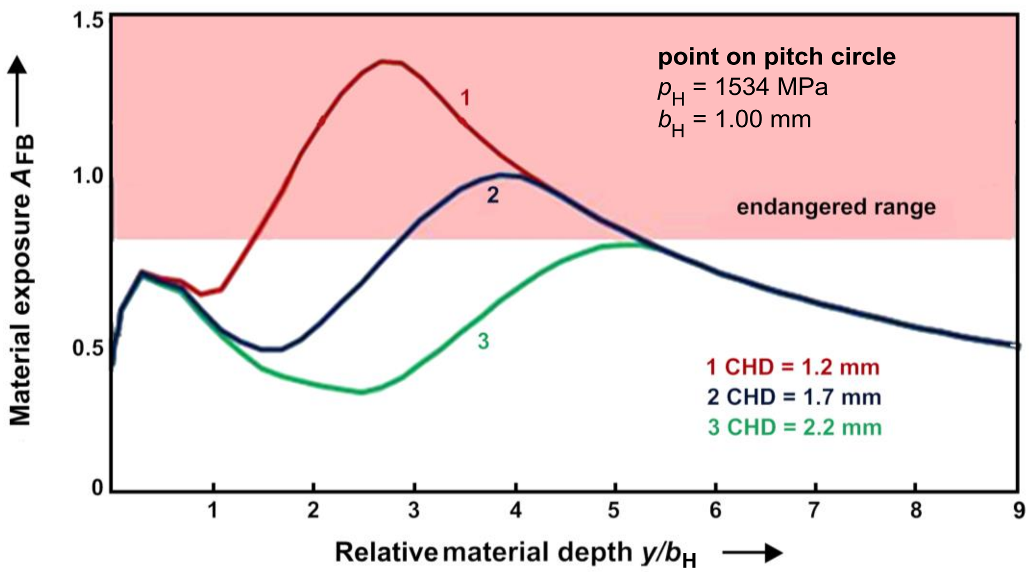


Figure 7. Influence of different CHD values on material exposure A_{FB} and risk of tooth flank fracture [30] (p_H – local Hertzian contact stress; b_H – local semi-Hertzian contact width).

As a different hardness profile also influences the residual stresses - compressive residual stresses are assumed in the complete case carburized layer - not only the material strength but also the equivalent stress distribution are influenced by different CHDs, Figure 7(a). Obviously, the ratio between local equivalent stress and local material strength is more critical with a smaller CHD and in this case is most unfavorable at a certain material depth that is close to the case-core interface. Consequently, CHD is not only an important parameter for pitting and bending strength of gears, but may also strongly contribute to minimizing the risk of crack initiation below the surface and thereby reduce the risk of failures due to tooth flank fracture, Figure 7(b). Furthermore, it is obvious that increasing the core strength of the gear material may contribute to reducing the risk of a failure initiation at greater material depth.

Requirements on Material Properties for Large Gear Sizes

An increased case hardening depth required for large gear sizes correlates with an increased carburizing time. Longer carburizing times will affect the bulk material properties and may result in special demands on the material characteristics for large sized gears. Some major requirements for optimized materials with special regard to large gear applications are summarized below:

- Case Hardening Depth (CHD): adequate CHD is necessary to achieve the required fatigue strength in the case and at the core: effects shown in Figure 6 and Figure 7; the gear material has to be suitable for long heat treatment process times to achieve the high CHD required for large gears;

- Surface Hardness: a minimum surface hardness of 660 HV (58 HRC) is required according to existing standards in order to achieve allowable stress numbers for pitting and bending resistance of quality levels MQ and ME; higher surface hardness values do not increase fatigue resistance, but make machinability more difficult; in contrast, wear resistance of the surface typically increases with higher surface hardness;

- Core Tensile Strength and Toughness: increased core hardness is known specifically to influence the tooth root bending strength; higher core toughness allows higher core hardness for optimized root bending strength; furthermore, increased core strength and toughness are assumed to reduce the risk of tooth flank fracture damage. Gear steels with improved hardenability are required to achieve the desired properties for large gears;

- Microstructure and Grain Size: fine acicular martensite in the case hardened region and fine acicular martensite and bainite in the core are required for optimized load carrying capacities; fine grain size, especially ASTM 8 and finer, is known to positively impact gear flank and tooth root load carrying capacity; specific alloying additions are required to ensure grain size stability and a fine microstructure, even at long carburization process times;

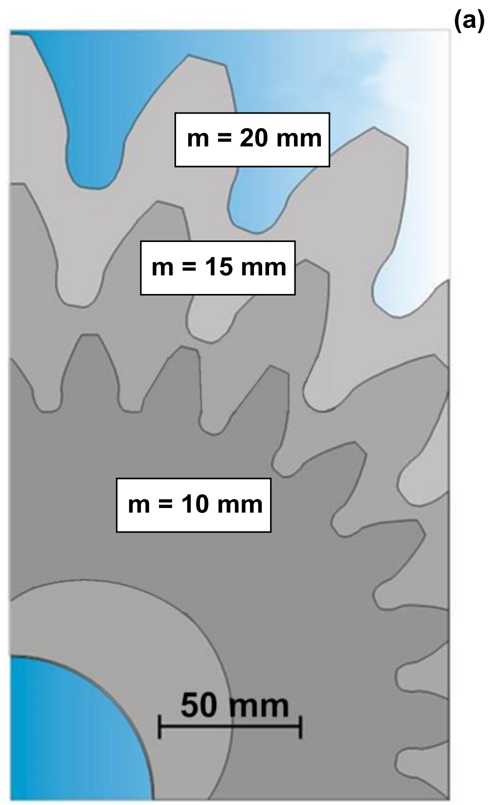
- Residual Austenite: a certain amount of retained austenite in the case hardened region is assumed to be beneficial for micropitting load capacity and may also contribute to an improved pitting strength. This is due to the ductility of the residual austenite. Higher amounts of residual austenite may reduce case hardness and bending strength; up to 25% finely dispersed retained austenite is allowable according to existing gear standards;

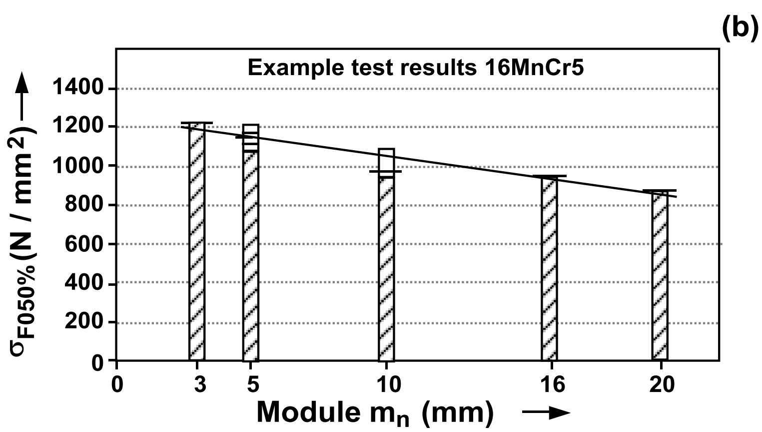
- Cleanness: non-metallic inclusions are known to act as local stress raisers; depending on inclusion size and chemical composition, the gear load carrying capacity, especially in consideration of the risk of a crack initiation below the surface, may be influenced; as the highly stressed material volume increases with gear size, the probability of undesirable inclusions being located in critical material volumes is increased; consequently this results in high demands on cleanness of gear material, especially for large gears;

- Area Reduction Ratio, Material Homogeneity and Intergranular Oxidation Depth: are further parameters that gain special importance for large gears; requirements according to existing gear standards have to be fulfilled even for larger gear sizes; intergranular oxidation can act as a fatigue fracture initiation site and may reduce the fatigue strength of the tooth;

- Hardenability: improved hardenability of the gear material is a basic requirement to achieve several of the above described properties for large gears.

Figure 8 demonstrates the influence of gear size on the tooth root bending strength. Basically, allowable stress numbers decrease with increasing gear size due to different size effects. Nevertheless, the results clearly demonstrate that, for large gear sizes, gear materials with higher hardenability (17CrNiMo6, 17NiCrMo14) achieve significantly higher bending strength values, compared to gear materials with lower hardenability (16MnCr5). The influence of material hardenability on gear strength is higher at larger gear sizes. Consequently, appropriate alloying additions to achieve a high material hardenability and to ensure adequate material characteristics are essential for high performance carburizing steels, in order to meet the requirements of large sized gears and to provide a sufficiently high gear load carrying capacity.





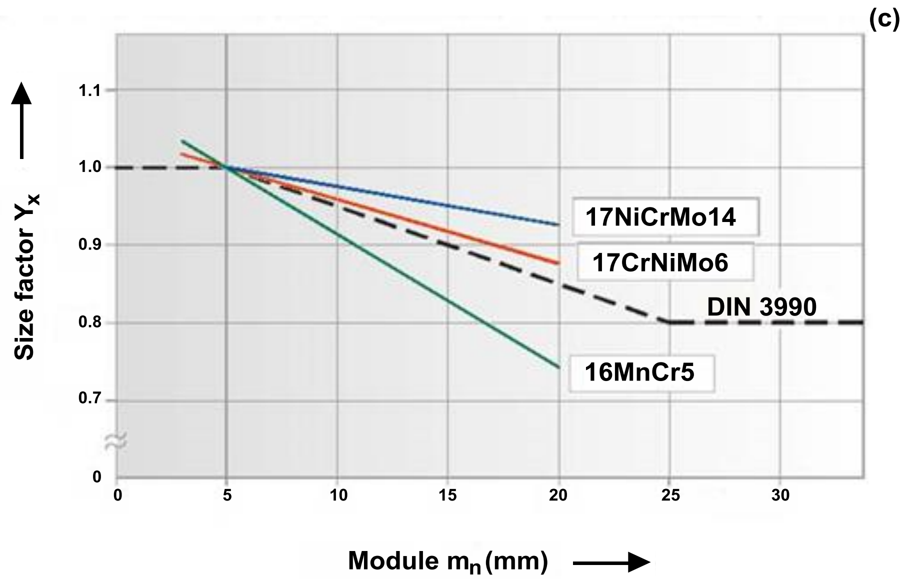


Figure 8. Influence of gear size on tooth root bending strength for gear materials with different hardenabilities; (a) examples of investigated test gears, (b) experimentally determined tooth root endurance limit for material 16MnCr5 depending on gear size, (c) experimentally determined size factor for tooth root bending strength for different gear materials [32] (m_n - gear module; Y_X – size factor for tooth root bending strength; $\sigma_{F050\%}$ - nominal tooth root bending stress at endurance life for 50% failure probability). Size factor is defined in DIN 3990-5 and ISO6336-5.

Steel grade 18CrNiMo7-6 (1.6587) has been selected as a performance reference material for the following investigations, since this grade currently is being widely used for demanding gear applications in Europe. The task was to modify the main alloying elements in such a way as to achieve either the same performance at lower alloy cost or better performance at similar alloy cost. The following approach is considered to be relevant in this respect:

- Improving hardenability;
- Increasing core tensile strength and toughness;
- Increasing fatigue strength in both case and core;
- Reducing quench distortion and thus detrimental tensile residual stresses;
- Improving microstructural stability to withstand elevated temperatures during manufacturing and service.

A fundamental way to deal with these issues is to adjust the chemical composition of the carburizing steel. Accordingly, the chemical composition of carburizing steels can be further developed to achieve the above goals using the following guidelines:

- Minimize intergranular oxidation → reduce Si, Mn, and Cr;
- Prevent MnS inclusions → reduce S, limit Mn;
- Prevent TiN inclusions → control Ti / N wt.% ratio close to 3.4;
- Improve hardenability → increase Mo;
- Minimize segregation → increase Mo and limit Mn levels

- Improve toughness → increase Ni and Mo;
- Refine and homogenize grain size → balance Nb, Ti, Al and N microalloying additions;
- Strengthen grain boundaries → reduce P and S, add Mo and Nb;
- Nano-precipitation to improve resistance to hydrogen embrittlement → add Nb.

Some developments of improved gear steels have focused on high nickel additions and reduced molybdenum content, Figure 9. Although this approach provides an elevated core strength and generally high toughness, the hardness in the near surface zone can be too low as nickel is a very efficient austenite stabilizer. On the other hand, raising the carbon and molybdenum contents, optionally in combination with microalloying elements, shifts the hardenability curve entirely upwards, thus providing a safety margin against local overloading. This second approach may lead to lower toughness, especially when the nickel content is reduced. However, refining and homogenizing the martensitic microstructure (packet size) can regain toughness. It was shown for 18CrNiMo7-6 that below an average martensite packet size of 20 µm the impact toughness strongly increases [10]. Since the packet size strongly correlates with the prior austenite grain size [10,11], control and refinement of the latter across the entire processing chain is an appropriate means of improving toughness.

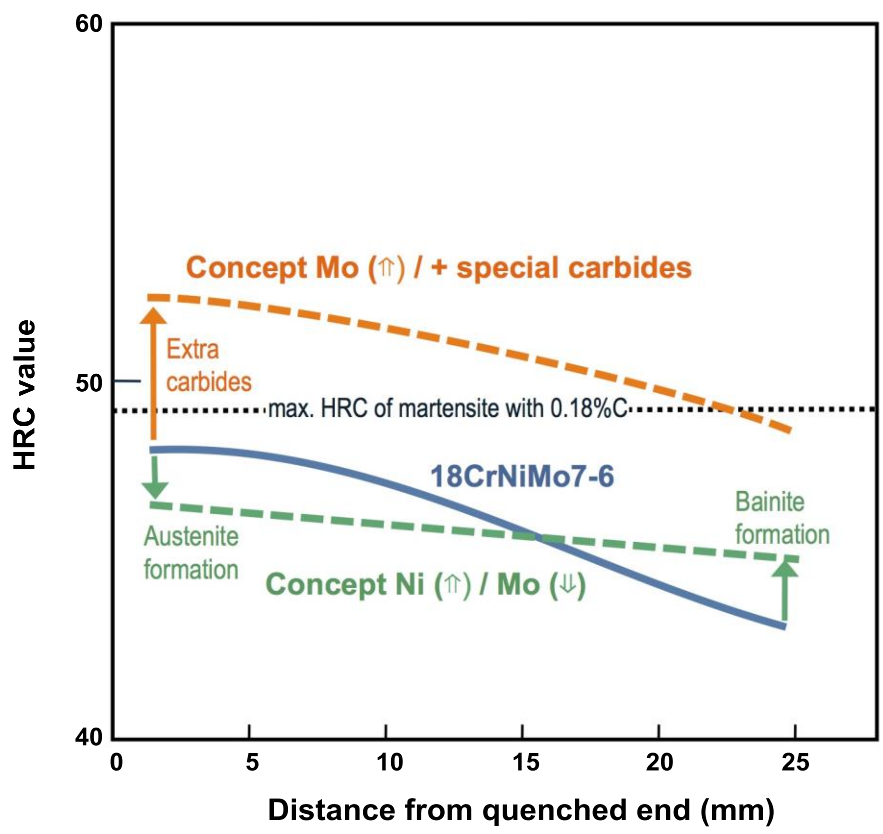


Figure 9. Effect of modified alloy concepts on the hardenability compared to the 18CrNiMo7-6 reference material.

Controlling Grain Size in Carburizing Steels

Many studies have indicated that prior austenite grain size control in carburizing steels can be effectively achieved by using niobium microalloying in combination with other microalloys, such as titanium, aluminum and nitrogen [12-19]. The alloying concepts developed have generally been aimed at refinement and homogenization of the grain size under standard case carburizing conditions. Furthermore, it has been demonstrated that high temperature carburizing becomes possible without violating grain size restrictions, thus allowing a faster furnace throughput. This is particularly beneficial when a larger case depth is required as in gears for trucks and heavy machinery. Additionally, a production concept for fine-grained carburizing steel has been developed based on an aluminum-free melt. This is to fully eliminate brittle alumina type inclusions which deteriorate toughness and fatigue resistance in the steel.

The restriction of grain coarsening is based on a pinning effect of precipitates on the austenite grain boundary. For efficient grain boundary pinning a suitable size and distribution of precipitates are necessary, which again depends on the prior thermochemical treatment, as well as the carburizing temperature. Above a critical carburizing temperature, the precipitates coarsen or dissolve and the pinning effect is lost. It appears to be most efficient to keep as much as possible of the microalloy content in solid solution prior to thermochemical processing, which can then precipitate as fine and homogeneously distributed particles during heating to the carburizing temperature. Niobium has the beneficial characteristic of low solubility in such steels, similar to titanium, providing temperature-stable precipitates. However, niobium has a lower affinity for nitrogen and contrary to titanium does not form coarse nitrides. Also, its precipitation kinetics are slower so that niobium remains in solution longer forming finer and more dispersed precipitates. It was also found that mixed precipitates of niobium, titanium and nitrogen are more resistant to dissolution at very high austenitizing temperatures. Therefore, a microalloy combination of low titanium (sub-stoichiometric to nitrogen) and niobium in the range of 0.03 to 0.1% has been proven to be most efficient.

Adding niobium in combination with titanium to the reference grade, 18CrNiMo7-6, has a marked effect on the grain size distribution as shown in Figure 10. Not only is the grain size generally much finer, but also the scatter band is narrower. The microalloyed variant safely avoids prohibited grain sizes despite the high carburizing temperature (1030 °C) and the long duration (25 hours). Similar good results of grain size stability have been obtained with modified variants of 25MoCr4 and 20CrMo5 grades, Figure 11. The niobium and titanium dual microalloyed 25MoCr4 variant reveals resistance to coarsening up to 1050 °C carburizing temperature, whereas the Nb-only microalloyed 20CrMo5 variant is stable up to 1000 °C. The data indicate that for very high carburizing temperatures, addition of multiple microalloys appears to increase the temperature stability of pinning precipitates. However, under standard carburizing conditions below 1000 °C, the Nb-only microalloyed concept exhibits a very fine austenite grain size with a moderate grain size scatter band.

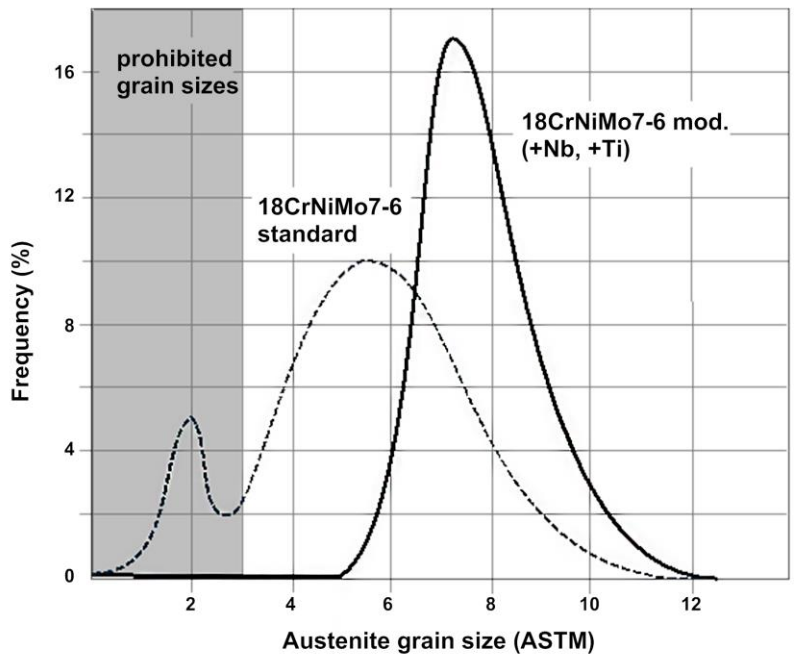


Figure 10. Grain size distribution of a Nb+Ti microalloyed 18CrNiMo7-6 (1.6587) heat compared to a conventional analysis (carburizing conditions: 1030 °C/25 h).

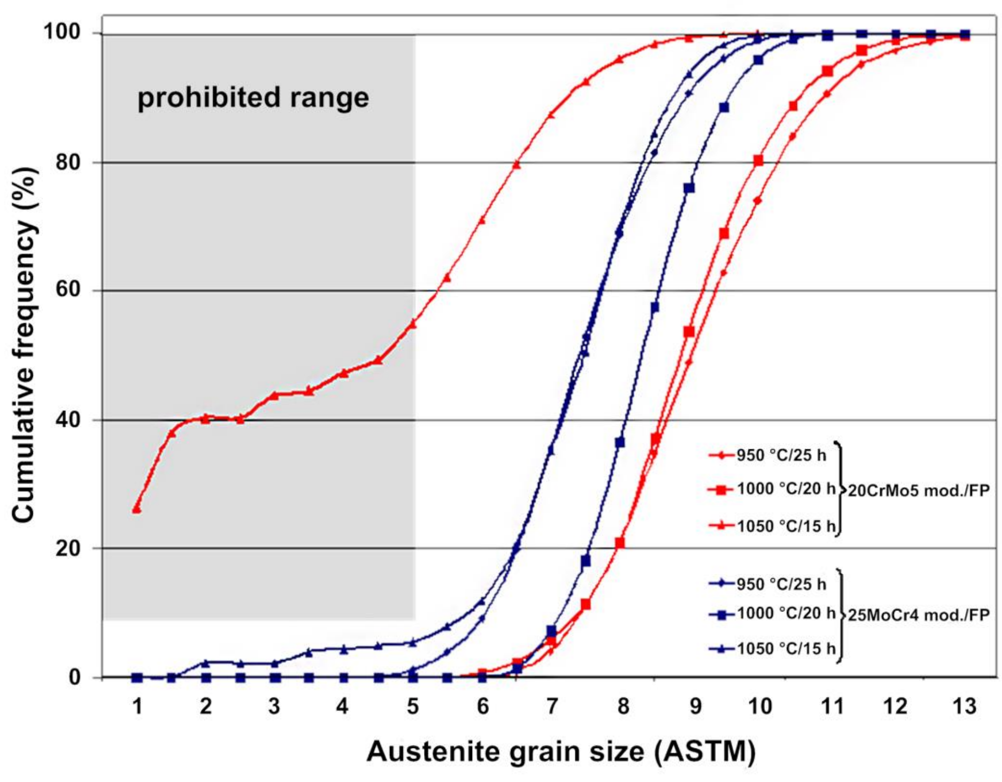


Figure 11. Grain size stability under various carburizing conditions for Nb-microalloyed 20CrMo5 (1.7264) and Nb+Ti microalloyed 25CrMo4 (1.7325).

The martensite–start temperature depends on the austenite grain size [20]. The smaller the austenite grain size, the lower is the martensite start temperature. In a mixed grain size structure transformation can occur locally at different temperatures. This situation will lead to the generation of residual stresses due to the volume change when the microstructure transforms from austenite to martensite. The earlier formed martensite islands cannot plastically accommodate the transformation volume change of the later formed martensite islands. Hence, the imbalance of elastic stresses causes a macroscopic distortion of the quenched component. It has been experimentally confirmed that a larger grain size scatter results in increased distortion, Figure 12 [21]. The distortion has to be corrected by straightening or hard machining. This is not only costly, but also reduces the thickness of the case carburized layer when performing hard machining. Furthermore, residual stresses are additive to the applied load stresses. Tensile residual stresses can cause premature failure, for instance under fatigue conditions.

Consequently, microalloying of case carburizing steel, leading to reduced grain size scatter as demonstrated above, is expected to reduce quench distortions. This could indeed be verified for components manufactured from the modified variant of 25MoCr4 (320 ppm Nb, 90 ppm Ti, 160 ppm N) shown in Figure 11. The material was continuously cast into bar. The bar was FP (ferrite/pearlite) annealed before cold extrusion and then again FP annealed. Carburization occurred at 980 °C for 195 minutes to a target case depth of 0.95 mm with a total furnace residence time of 400 minutes. The components were then quenched in an oil bath (Isorapid 277) and held at 60 °C. Subsequently, part distortion was characterized by roundness deviation measurements at five positions as shown in Figure 13. It is obvious that the microalloyed variant has much lower roundness deviation, as compared to the standard alloy. At each measuring position the deviation was reduced by approximately 50%, resulting in a similar reduction of rectification. The cost savings achieved by such reduced rectification by straightening or hard machining are likely to compensate for the cost of the microalloys. If the available equipment allows high temperature carburizing, significant process time savings can be realized. For instance, for producing a target case depth of 1.5 mm the total treatment cycle time can be reduced by 25 and 40 percent when the carburizing temperature is raised to 980 °C and 1030 °C, respectively, as compared to a standard carburizing temperature of 930 °C.

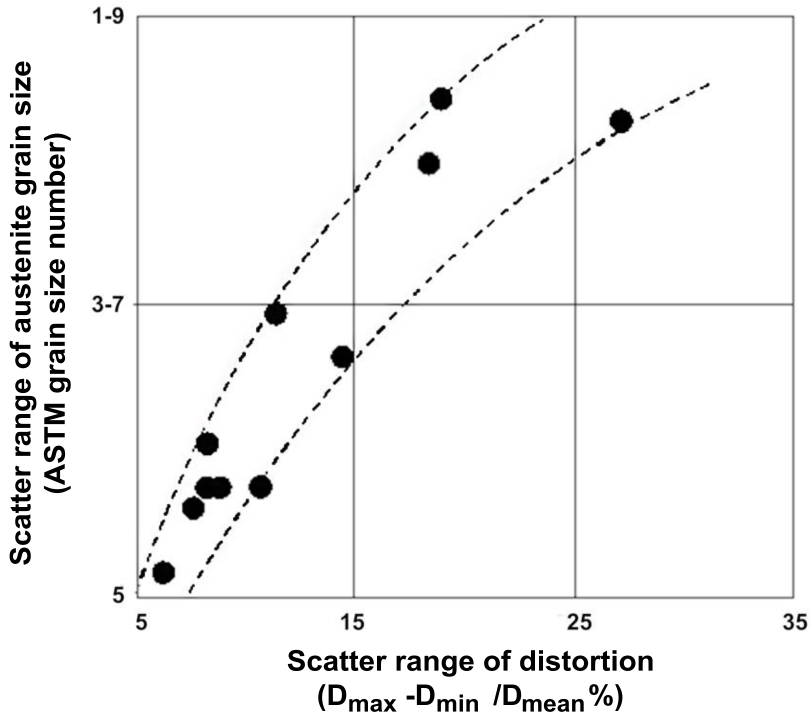


Figure 12. Dependency of distortion scattering after heat treatment on the mean prior austenite grain size scattering in the steel 16MnCr5 (1.7131) [21].

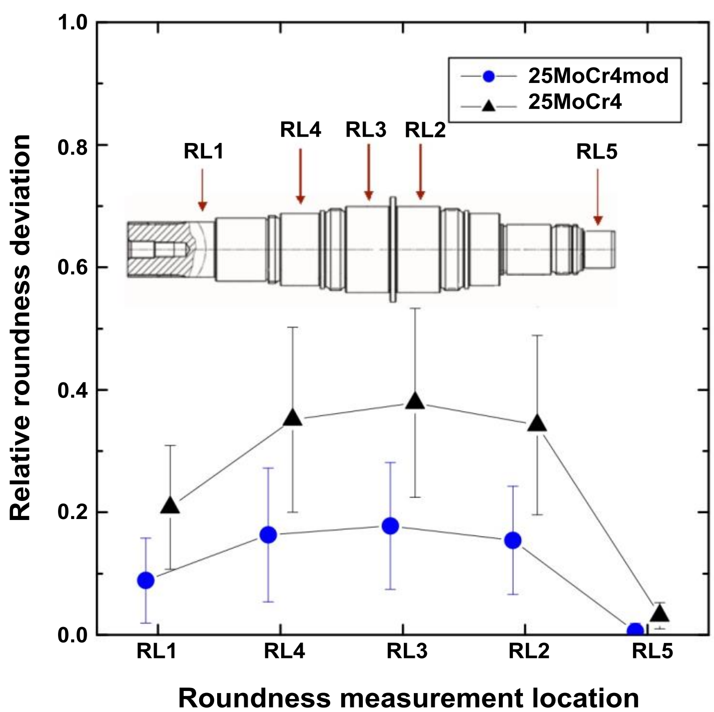


Figure 13. Roundness deviation of a heat-treated transmission shaft measured at five positions for standard 25MoCr4 (1.7325) and 25MoCr4 modified by Nb+Ti microalloying.

Increasing Hardenability and Tempering Resistance

As outlined above, it is of great interest to avoid a steep hardness gradient in the transition area from the case layer to the core material. Therefore, the hardenability of the alloy must be improved. Several alloying elements, besides carbon, contribute to hardenability, including molybdenum, manganese, chromium and nickel, as well as boron. For cost reduction reasons, alloys using higher manganese and chromium additions, eventually combined with boron microalloying have been favored for many gear applications. However, such reduced cost alloy concepts, although providing good hardenability, have limitations in terms of toughness and tempering resistance. Additionally, the limitation of intergranular oxidation requires manganese, chromium and silicon levels to be reduced. In some extreme cases, alloy producers have developed highly alloyed steels for those applications where transmission failure causes high replacement and outage costs. An example is 15NiMoCr10-4 (C:0.15%, Si:1.1%, Cr:1%, Mo:2% and Ni:2.5%), which is used in high end applications eg. in aerospace or Formula-1 gears. However, such steel requires special melting technology and is not widely available. Comparing this steel to another high-nickel steel (14NiCrMo13-4), the increase of the molybdenum content from 0.25% to 2.0% brings about a significant improvement of hardenability, surface hardness and tempering resistance [22], Figure 14. The high tempering resistance of the material brings two important advantages. Firstly, it allows duplex treatments, ie. the case hardened surface undergoes a second treatment such as Physical Vapour Deposition (PVD) coating or plasma nitriding (PN) to further increase the surface hardness. These treatments are usually performed in a temperature window of 300 to 500 °C. It is thus a prerequisite that the hardness obtained in the underlying material after quenching from the carburizing temperature is not degraded by the subsequent heating cycle. Secondly, many conventional case carburizing steel grades are restricted to a maximum operating temperature of 120 to 160 °C. A steel grade with high tempering resistance can be operated at higher temperatures without degrading. Elevated operating temperatures may occur for instance by frictional heating if the transmission gear box experiences lubrication problems.

Good tempering resistance in a typical gear steel base alloy can also be achieved with lower molybdenum additions as indicated in Figure 15. Even at levels of 0.5-0.7% a molybdenum addition provides good resistance against softening for tempering parameters (HP – Holloman parameter) up to around 16 x 10^3. Resistance to softening at tempering parameters below 16 x 10^3 means that a secondary treatment at a temperature of 450 °C for up to 10 hours should be possible. This condition is typical for plasma nitriding.

Microalloying with niobium further enhances the tempering resistance, in a synergistic effect with molybdenum. Molybdenum and niobium have, to some extent, similar metallurgical effects. Both exert strong solute drag on grain boundaries as well as at dislocations [23] and also lower the activity of carbon [24]. These fundamental effects are evidenced by delayed recovery and/or recrystallization, as well as a reduced rate of pearlite growth, thus increasing hardenability. The solubilities of both elements in austenite are, however, very different. Molybdenum has a high solubility [25], whereas that of niobium is low [26]. Therefore, niobium precipitates as NbC particles at relatively high temperatures. Manganese, chromium and particularly molybdenum increase the solubility of niobium in austenite [27]. Accordingly, more niobium will be in solution after quenching from the austenitizing temperature and thus available for fine precipitation during the tempering treatment, which acts to resist softening.

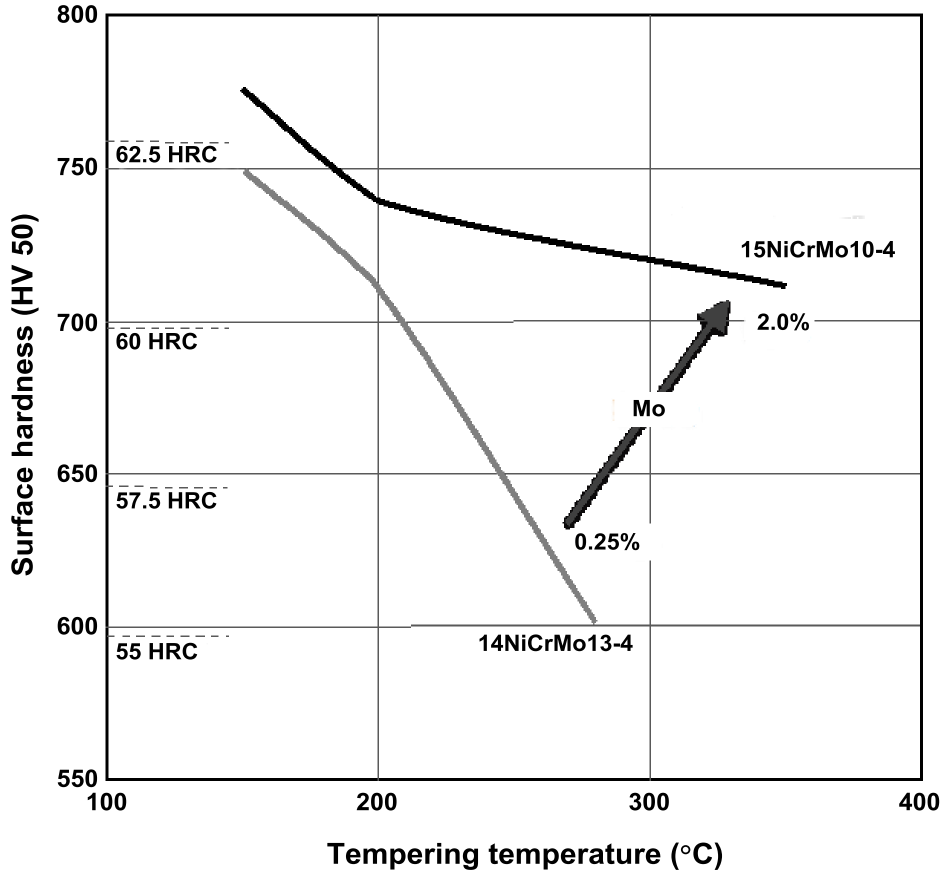


Figure 14. Surface hardness of the carburized layer in relation to tempering temperature and effect of increased molybdenum content.

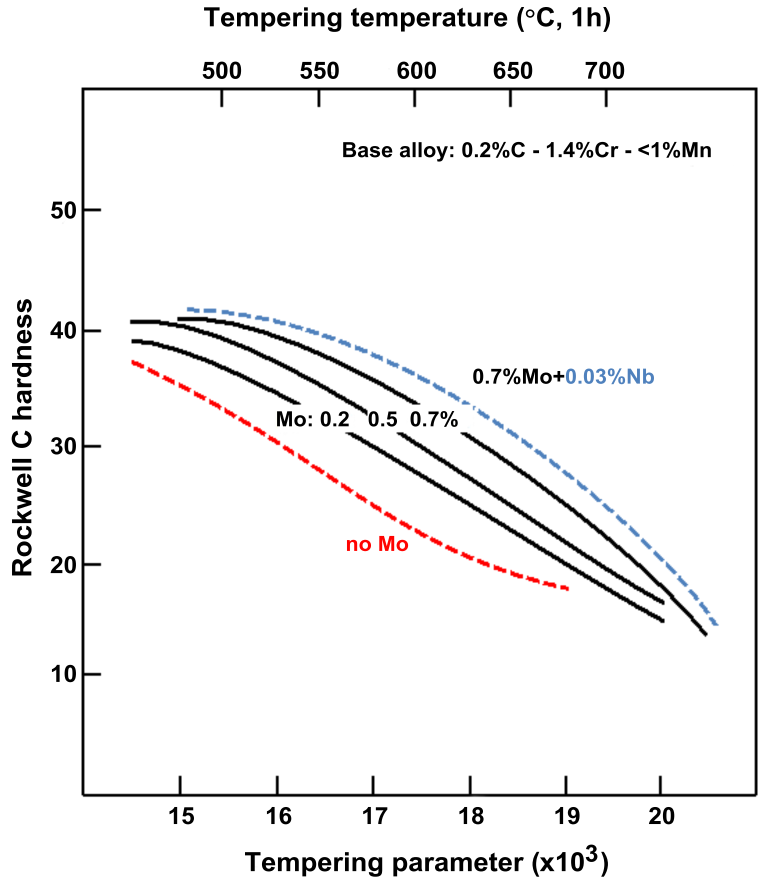


Figure 15. Effect of tempering resistance as a function of the molybdenum content and synergistic effect with niobium (HP = T x (20 + log t) x 10^{-3} [T in K, t in h]).

Modification and Testing of Carburizing Steels

Based on the individual and synergistic effects of alloying elements described above, the intended processing route and the desired property profile, two modified alloy concepts have been designed, Table II, for a full scale production trial including gear running tests. One of the alloy designs (concept V1) can be considered as a modified 20MnCr5 grade. It is aimed at producing a higher performance than that of 18CrNiMo7-6 at similar alloy cost. The content of carbon is increased for higher maximum hardness, while molybdenum and nickel are added for increased hardenability and tempering resistance. The other alloy design (concept V2) developed can be seen as a modified 20CrMo5 grade with added nickel, which has a lower total alloy cost than 18CrNiMo7-6, yet aiming for similar performance. In both concepts niobium microalloying is used for austenite grain size control. The mechanical properties of both novel case carburizing steels, obtained after heat treatment, indeed realize the desired property levels, Table III. The hardenability of concept V1 is superior to that of 18CrNiMo17-6, whereas that of concept V2 is within the hardenability range of the reference steel. After an austenitizing treatment at 880 °C for 2 hours followed by quenching in oil and holding at 180 °C for 2 hours concept V1 clearly shows better tensile and fatigue strength, while concept V2 nearly exactly matches the strength of the reference grade. The toughness of both developed steels is lower than that of 18CrNiMo7-6 due to the reduced nickel content, yet remains at an acceptable level.

Table II. Chemical Composition of Developed Case Carburizing Steels

Steel Grade	C	Si	Mn	Cr	Mo	Ni	Nb
Concept V1	0.26	0.12	1.46	1.23	0.54	0.91	0.03
Concept V2	0.21	0.25	1.17	1.15	0.21	0.22	0.04

Table III. Mechanical Properties of Developed Case Carburizing Steels
(Hardened at 880 °C/2 h + Oil Quench/180 °C/2 h)

Property	Concept V1	Concept V2	18CrNiMo7-6
Tensile strength, R_m (MPa)	1758	1182	1182
Impact energy, A_v (J) at RT	47	55	80
Rotating fatigue limit $\sigma_{(50\%\ @N=10^7)}$ (MPa)	722	491	510
Hardenability at 11 mm (HRC)	51	44	41
Hardenability at 25 mm (HRC)	50	36	36

The heat treatment behavior of the developed alloys has been tested using a carburizing process at 1030 °C to a nominal case depth range of 0.95 to 1.2 mm. This depth requirement originated from the gear running tests to be executed with 5 mm module gears actually requiring 0.75 to 1.0 mm case depth. The additional case depth was intended to compensate for grinding losses during hard machining of the carburized gear. For determining the depth of the case layer, a limit hardness of 550 HV was defined according to ISO 6336-5. The target surface hardness was set at 670 HV as minimum. Additionally, secondary plasma nitriding treatments have been performed at 400 and 440 °C, respectively. Table IV summarizes the hardness data for the various pilot heat treatments. In the as-quenched condition, after carburizing, both grades fulfill the requirements. Both alloy concepts sustain a tempering treatment at 200 °C. Concept V2, however, does not retain sufficient hardness after the plasma nitriding treatment. On the contrary, concept V1, due to its increased tempering resistance, shows a very high surface hardness of around 1000 HV after plasma nitriding, whereas the core hardness is reduced. Nevertheless, a core hardness of more than 400 HV is still a high value. It thus appears that concept V1, with some further optimization, has the potential of fulfilling the case depth requirements at secondary treatment temperatures up to 440 °C. A slight increase of the molybdenum content towards 0.7%, Figure 9, and fine-tuning of the microalloy addition are thought to be the most promising way of achieving this.

Table IV. Hardness Characteristics after Various Heat Treatments

Treatment after carburizing at 1030 °C	**Concept V1 (20MnCr5 mod.)**			**Concept V2 (20CrMo5 mod.)**		
	Surface (HV 1)	**Core (HV 10)**	**CHD_{550HV1} (mm)**	**Surface (HV 1)**	**Core (HV 10)**	**CHD_{550HV1} (mm)**
As-quenched	769	544	2.04	786	408	1.28
Freezing -70 °C/2 h Tempering 200 °C/2 h	717	505	1.53	-	-	-
Tempering 200 °C/2 h	-	-	-	672	430	1.20
Plasma nitriding at 400 °C	994	432	0.8	707	416	0.25
Plasma nitriding at 440 °C	1009	422	0.35	570	395	0.1

Operational performance of the developed steel grades (V1 and V2) was tested and benchmarked at FZG, TU München, Germany. The tooth root load carrying capacity was investigated in a pulsator rig, Figure 16. Investigations on the flank load carrying capacity were performed by running tests on a back-to-back gear test rig, Figure 17, according to DIN ISO 14635-1 [28]. The test gears for these investigations were case hardened after gear milling. Subsequent to case carburizing, the test gears were mechanically cleaned by shot blasting. The flanks, as well as the tooth roots of the test gears for the investigations on the tooth root bending strength, were not ground. The gear flanks of the test gears for the gear running tests were finally ground to a gear quality of $Q \leq 5$ (DIN 3962) and a surface roughness Ra ≤0.3 µm. In order to reduce the effects of premature contact resulting from tip mesh interference due to elastic tooth deflections under load, profile modifications in the form of a tip relief were applied to the gears for the running tests.

For the experimental investigations on the tooth root bending strength, standard pulsator test gears with a gear module $m_n = 5$ mm, number of teeth $z = 24$ and face width $b = 30$ mm were used. For the running tests, spur gears with a module $m_n = 5$ mm, a gear ratio of 17/18 and a face width $b = 14$ mm were used. Both test gear types are typical of those used for the examination respectively of bending strength and pitting load capacity of case carburized gears and are in accordance with the requirements of ISO 6336 [6] for reference test gears.

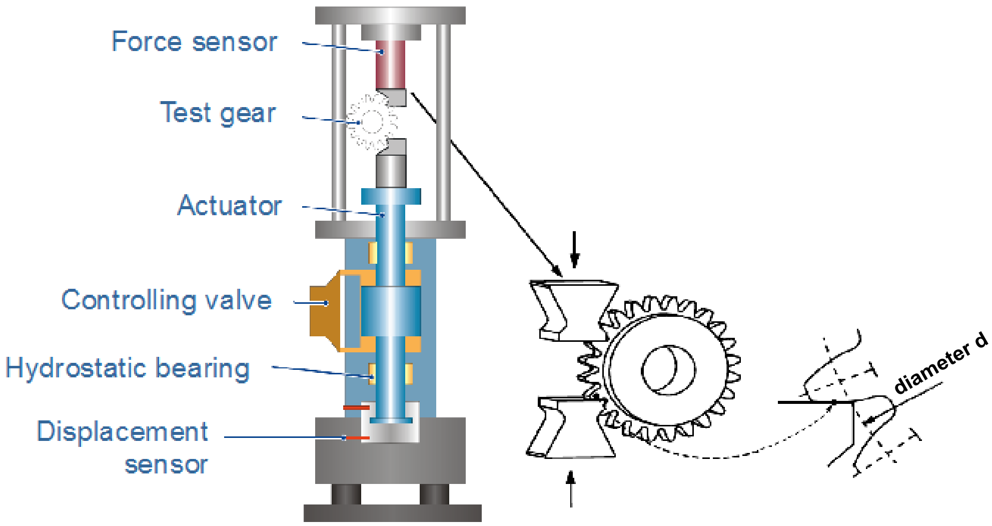


Figure 16. Schematic illustration of a pulsator test rig for investigation of the tooth root load carrying capacity.

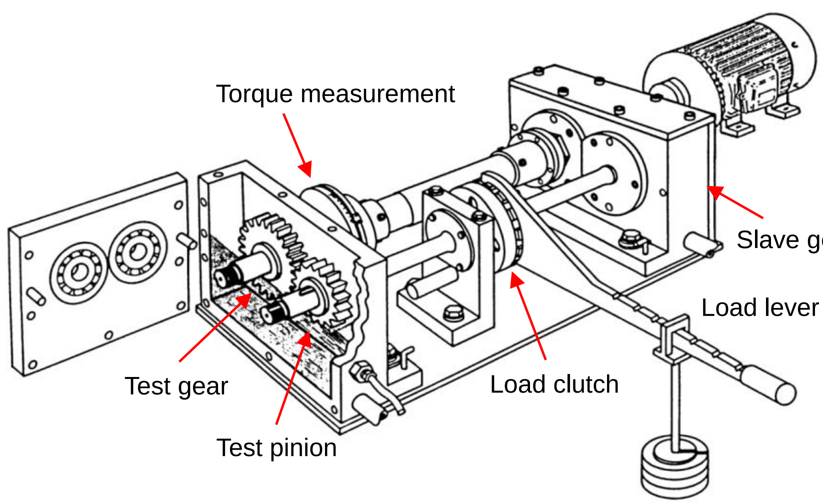


Figure 17. FZG standard back-to-back gear test rig for investigation of the flank load carrying capacity.

The tooth root load carrying capacity is one of the determining factors in gear design. Besides the strength of the material itself, the existing state of stress (load induced stresses and residual stresses) significantly influences the tooth root load carrying capacity. The mechanical cleaning procedure by shot blasting, as used in this test program, introduces compressive stresses in the sub-surface zone and is beneficial for fatigue resistance, see also Figure 18 [33]. The current tests were carried out under constant pulsating load and continued until the limiting number of load cycles ($6x10^6$) was reached or tooth root breakage occurred. For each alloy concept, a complete S-N curve was determined based on approximately 25 test points. The endurance strength level was determined using the “staircase method” based on at least 10 data points for each alloy concept. The pulsating load at the endurance limit was estimated for a failure probability of 50 percent. The high-cycle fatigue part of the S-N curve was determined from approximately ten valid tests for each variant. The conversion of the pulsating load into the resulting tooth root stress was carried out according to DIN 3990 part 3 [5]. The allowable stress numbers for bending, σ_{Flim} and σ_{FE}, given in DIN 3990/ISO 6336 [5,6] are valid for standard reference test gears at standard test conditions in a gear running test and a failure probability of 1 percent. Therefore, the test results from the pulsator tests were converted to these conditions according to the state-of-the-art approaches.

The results obtained from these tests are shown in Table V. Case carburized alloy V1 (20MnCr5 mod.) clearly exhibits a higher tooth root bending strength than the case carburized alloy V2 (20CrMo5 mod.) as can be expected from the hardness characteristics. It has been established that surface hardened gears of high load capacity containing high residual compressive stresses in the surface layer due to shot peening, exhibit an increased risk of crack initiation below the surface [7]. In this respect, the cleanness of the material has a decisive influence. Furthermore, it is assumed that the microstructure and especially the ductility of the surface layer are also relevant in determining the cracking behavior. Alloy V1 did not show sub-surface crack initiation.

Table V. Characteristics of the Determined S-N-curves Concerning Tooth Root Bending Strength for 50% Failure Probability as well as Nominal and Allowable Bending Stress Numbers

Criterion	**Concept V1**	**Concept V2**
Nominal endurance tooth root bending stress for 50% failure probability (MPa)	1368	1072
Gradient of S-N curve at short fatigue life (50% failure probability)	28.1	8.8
Number of load cycles at inflection point (50% failure probability)	2,048,078	436,884
Nominal tooth root bending stress σ_{FE} (MPa)	1134	885
Nominal bending stress σ_{Flim} (MPa)	567	442
Cracking behavior in low-cycle fatigue range	Fractures with crack initiation at the surface	Fractures with crack initiation at the surface
Cracking behavior in high-cycle fatigue range	Fractures with crack initiation at the surface	Fractures with crack initiation below the surface

In Figure 18 the determined nominal bending stress numbers are compared to the nominal tooth root bending stress levels according to DIN 3990/ISO 6336 [5,6] and to the test results from several batches of two case hardened Western European standard steels determined under comparable test conditions [33]. A further performance benchmark of both developed alloys against established case carburizing alloys is shown in Figure 19. In this graphic, the grey shaded area indicates the typical performance range of European state-of-the-art carburizing grades, see also Figure 18. Additionally, some international carburizing grades that were tested by the same method are indicated. Figure 18 and Figure 19 prove that alloy V1 ranks on top (quality level ME) of the property field of established alloys according to DIN 3990 [5] and performs better than many more highly alloyed steel grades, including the reference grade 18CrNiMo7-6. Alloy V2 compares well with the state-of-the-art alloys achieving quality level MQ.

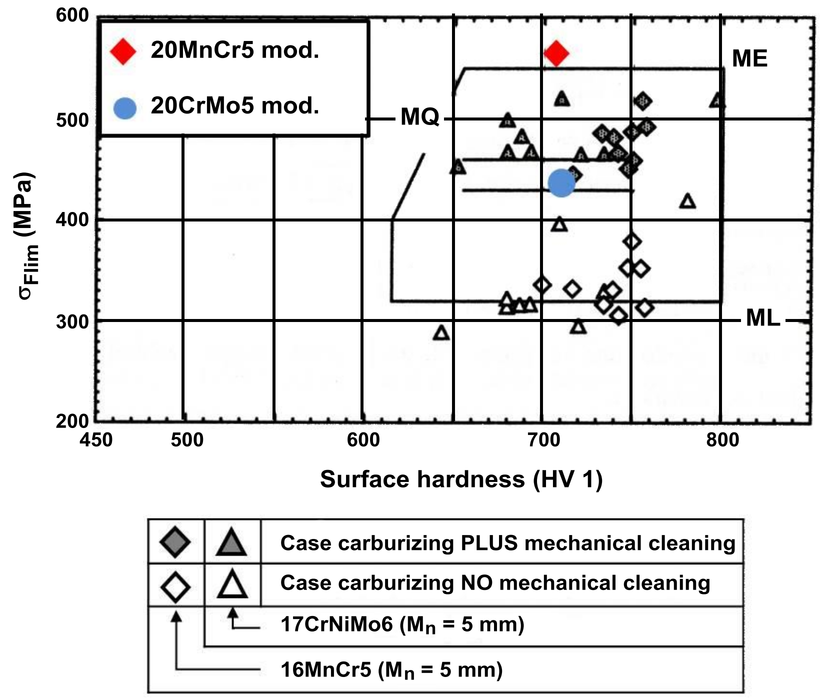


Figure 18. Comparison of the tooth root bending stress numbers of newly developed case carburized steels vs. strength levels of DIN 3990 and vs. results of reference steels determined under comparable test conditions [33].

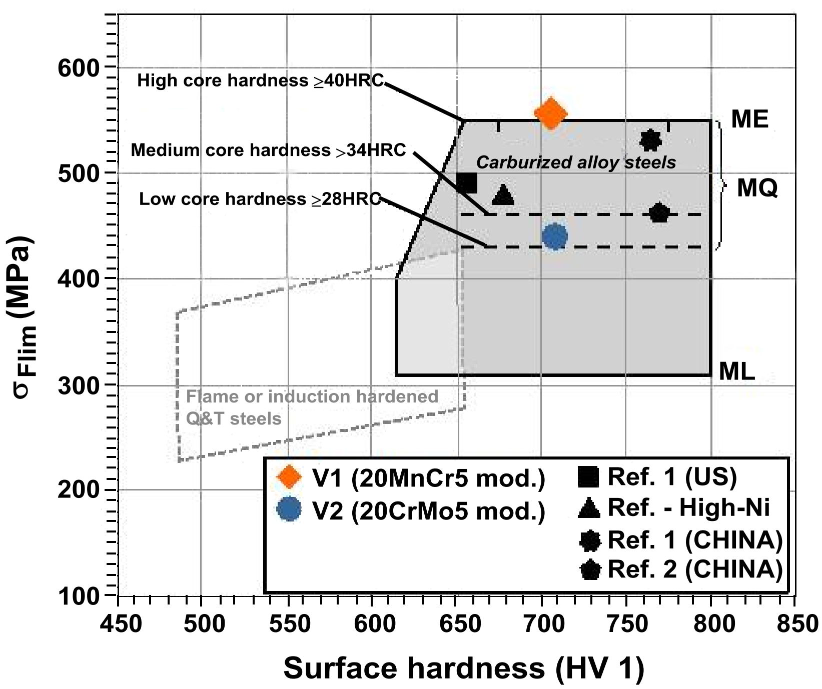


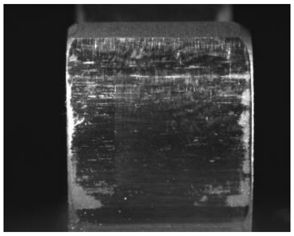
Figure 19. Comparison of the tooth root bending stress numbers of newly developed case carburized steels vs. some international case carburizing steels (see also Table I). (Note: Refs. 1 and 2 do not correspond to references in the current paper.)

In order to determine the pitting load capacity of the gear flank, repeated gear running tests in the high cycle, as well as the low cycle fatigue range were carried out [34]. The test rig was driven at a constant speed of 3000 rpm. All test runs were performed using oil spray lubrication (approx. 2 l/min into the tooth mesh) with FVA 3 + 4% Anglamol 99 (S-P-additive), a mineral oil of viscosity class ISO VG 100, and an oil temperature of 60 °C. Prior to each test run, a two-stage running-in period was performed. Under the described test conditions, six to eight test runs for each variant were scheduled at different load levels in order to determine the pitting load carrying capacity. The test runs were continued until either one of the failure criteria mentioned below was reached or the specified maximum number of load cycles was exceeded without failure. The test runs were regularly interrupted after a defined interval of load cycles in order to inspect the flank condition. According to the defined failure criteria, a test run was terminated when:

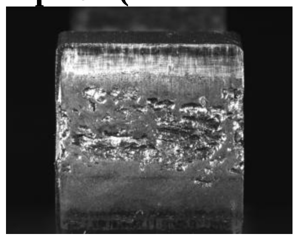
- Tooth breakage occurred;
- The flank area damaged by pitting exceeded about 4% of the working flank area of a single tooth or about 2% of the total working flank area;
- The mean profile deviation due to micropitting exceeded the limiting value of 15-20 μm;
- A minimum number of 50 x 10^6 load cycles was reached without damage.

After every test run, the flank condition was evaluated and documented by means of digital photographs, Figure 20. During all test runs of alloy V2, micropitting was observed on the flanks of the test pinion and test gear. However, the limiting criterion of a profile deviation f_{fm} >20 μm due to micropitting was not reached in any of the test runs. Normally, light micropitting leads to pitting failure at higher numbers of load cycles. Test gears made from alloy V1 indicated a significantly lower sensitivity to micropitting than the test gears made from alloy V2.

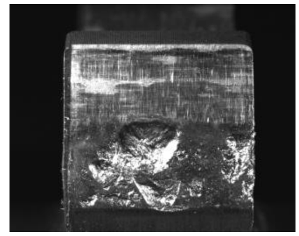
Concept V1 (20MnCr5 mod.)



σ_{H0} = 1598 N/mm², 51 x 10^6 load cycles

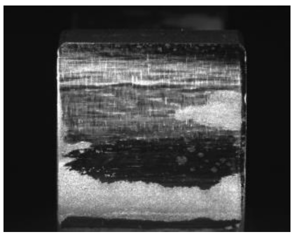


σ_{H0} = 1801 N/mm², 15 x 10^6 load cycles

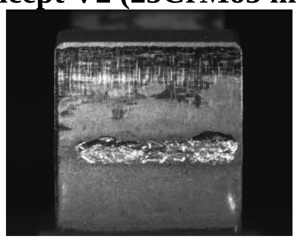


σ_{H0} = 1900 N/mm², 9 x 10^6 load cycles

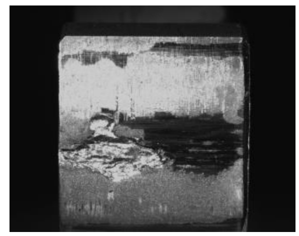
Concept V2 (25CrMo5 mod.)



σ_{H0} = 1495 N/mm², 51 x 10^6 load cycles



σ_{H0} = 1598 N/mm², 54 x 10^6 load cycles



σ_{H0} = 1801 N/mm², 12 x 10^6 load cycles

Figure 20. Examples of typical tooth flank condition at the end of the test runs for various nominal contact stresses σ_{H0} and load cycles

The gear running tests allow an approximate determination of the pinion torque at the endurance limit, as well as of the nominal contact stress number at the endurance limit for a failure probability of 50 percent. The allowable contact stress (σ_{Hlim}) representing the pitting load capacity with a failure probability of 1 percent is then calculated according to DIN 3990 [5]. Table VI summarizes the flank pitting load capacity limits determined for the two developed steel grades. A benchmark comparison of these data against the strength values for the different quality levels according to DIN 3990/ISO 6336, as well as for some reference data from literature [29] is shown in Figure 21. A further performance benchmark of both developed alloys against established case carburizing alloys is shown in Figure 22. Obviously, alloy V1 (20MnCr5 mod.) exhibits a very high pitting endurance limit and outperforms established alloys of quality level ME. The pitting endurance limit of alloy V2 (20CrMo5 mod.) is situated in the upper region of the established contact stress field for case hardened steels reaching quality level ME.

Table VI. Experimentally Determined Endurance Limit for Pitting

Criterion	Concept V1	Concept V2
Nominal endurance strength for 50% failure probability (MPa)	1699	1547
Allowable contact stress (MPa)	1793	1633

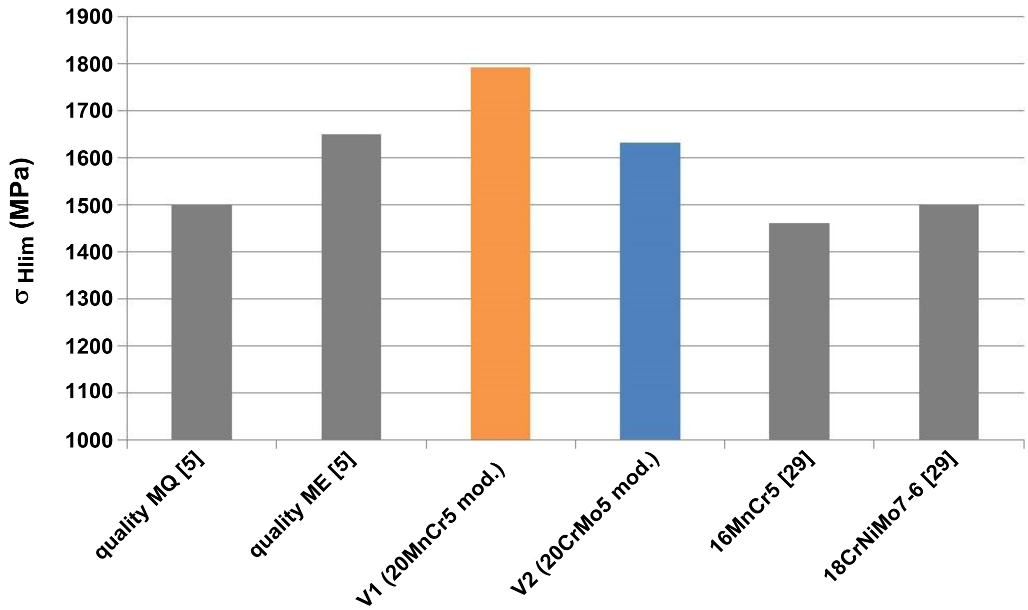


Figure 21. Comparison of determined pitting strength number of new case carburized steels vs. strength levels of DIN 3990 and literature data for reference steels.

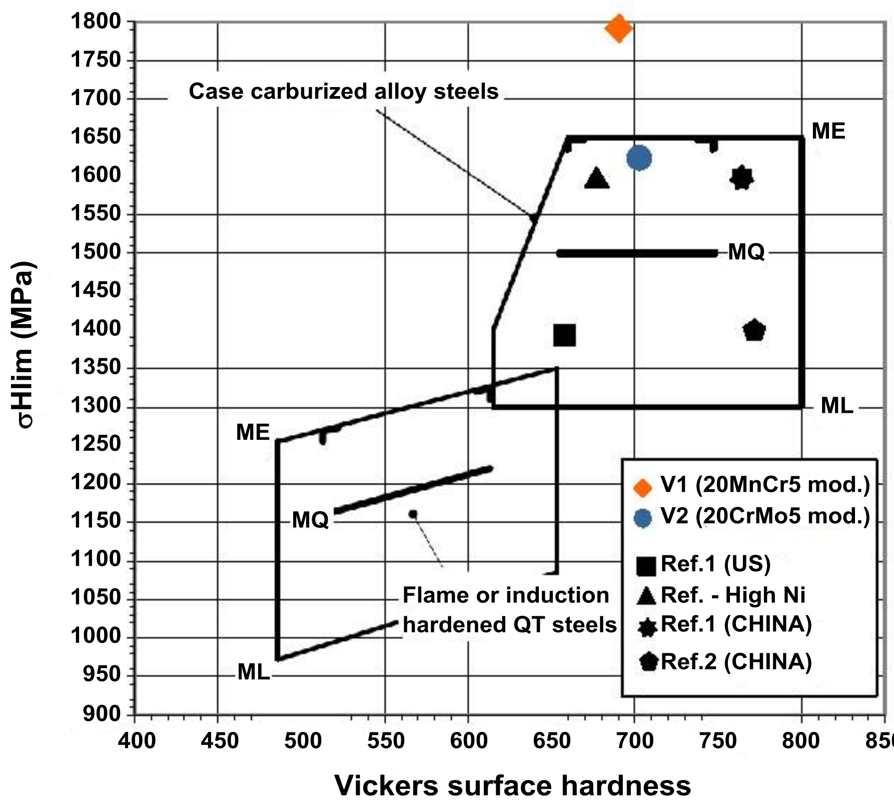


Figure 22. Comparison of pitting endurance strength number of new case carburized steels vs. strength levels of DIN 3990 and vs. some international case carburizing steels (see also Table I). (Note: Refs. 1 and 2 do not correspond to references in the current paper.)

The current results suggest that alloy V1 has the potential of providing an economically viable solution for highly loaded gears in heavy machinery and vehicles. Its use in vehicle transmission could enable downsizing of components, thus reducing weight. In larger transmissions, such as used in trucks and heavy machinery, its use could help avoid unexpected failure and promote extended warranty periods. The results from alloy V2 position it as a cost attractive alternative to the established premium grade 18CrNiMo7-6.

Conclusions

Recent and future application-driven demands challenge the performance of industrial and automotive gearboxes. Many parameters, such as material, heat treatment, gear design, machining and lubrication have to be considered for optimizing gearbox performance. In this paper the focus was on optimizing the alloy composition of case carburizing steels, particularly by the use of molybdenum and niobium as alloying elements.

Molybdenum alloying in case carburizing steels is established due to its strong hardenability effect. Yet, for alloy cost reasons, many attempts have been made in recent years to replace molybdenum fully or partially by other elements which increase hardenability.

The current results demonstrate, however, that molybdenum has several additional metallurgical benefits that are not provided by other hardenability enhancing elements.

Molybdenum significantly increases the tempering resistance, thus opening an opportunity for performing secondary heat treatments after case carburizing. The increased tempering resistance also makes gears less vulnerable to hot running in case of lubrication problems during operation.

It is also known that molybdenum enhances high angle grain boundary cohesion, thus obstructing intergranular crack propagation and hence retarding macroscopic damage.

Contrary to manganese, molybdenum does not have a strong tendency to segregate and it does not form inclusions. Furthermore, its use does not increase the sensitivity to intergranular oxidation, as is the case for manganese and chromium.

The present investigation has demonstrated that modifying standard alloys with a moderate addition of molybdenum (0.5-0.7 wt.%) can lead to significantly better performance in gear running tests compared with state-of-the-art alloys, including several high nickel steels.

Microalloying, and in particular the addition of niobium to case carburizing steels, has been gaining increasing interest over the years. The benefit is an improved control of grain size scatter at simultaneously reduced prior austenite grain size throughout the heat treatment processes. A finer and more homogeneous grain structure results in improved toughness, higher fatigue resistance and less distortion after heat treatment. Additionally, niobium further increases the tempering resistance provided by molybdenum, due to a synergistic metallurgical effect.

Recently, it has also become evident that grain refinement (prior austenite grain size) of martensitic steels by niobium microalloying, as well as its precipitation as nano-carbides, results in an increased resistance to hydrogen embrittlement.

These effects of microalloying with niobium gain increased importance, especially for highly loaded, large-size gears that require a greater case hardening depth and thus increased carburization times.

Based on the fundamental understanding of metallurgical effects of alloying elements in general, and molybdenum and niobium in particular, it is possible to modify existing case carburizing steels to give increased performance levels at acceptable alloy costs. It also becomes possible by applying innovative heat treatment processes to either increase production efficiency or performance.

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